APPENDIX A

METHODOLOGY USED IN THE ENVIRONMENTAL CONSEQUENCE ANALYSIS

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This appendix describes the methodology used in evaluating the environmental consequences of transporting Pu-238 fuel under normal and accident conditions under the proposed action. The focus is on potential accidents that could release the Pu-238 into the environment during handling and transport.

A.1 OVERVIEW OF METHODOLOGY

The radiological impacts of transporting radioactive materials include radiation doses and associated health effects due to external radiation from packages during normal transport and radioactive releases under accident conditions. Transportation accident risk may be defined as the consequences of an accident multiplied by the probability of that accident. The probabilities of occurrence of various accident severity categories are determined by the base accident rate for the mode and the conditional probability for the category. Accident severity is a function of the magnitudes of the impact, puncture, and thermal environments to which a package may be subjected during an accident. The base rate is multiplied by the conditional probability for a severity category to generate the overall accident probability of that severity category.

In the accident risk analysis, the consequences are determined based on the radionuclide contents of the material being shipped; the behavior of the package in each accident severity category; the dispersal of radioactive material that may be released from the package; and the doses to persons from the radioactive material. After the component risks are generated, they are summed and multiplied by a dose-conversion factor to estimate the health effects risk.

The RADTRAN computer code (currently version 4.0) developed by Sandia National Laboratories (Neuhauser, 1989) is commonly used to calculate the risks associated with the transport of radioactive materials by various modes, including truck and ship. The radiological consequences considered include those during incident-free transportation (due to external radiation) and under accident conditions (involving a release of radioactive materials to the environment). The exposed population groups considered include the crew, package handlers, and the general public along and off the transport links.

During incident-free transport, the radiological consequences will depend in part on the Transport Index (TI) value of the package and the surrounding population densities. The TI is a dose-rate index defined as the dose rate in millirem per hour at 1 meter from the package surface.

Under accident conditions, radiological consequences are calculated by assigning release fractions to each accident severity category for each chemically and physically distinct type of radionuclide. The release fraction is defined as that fraction of the radionuclide in the package that could be released in a given severity of accident. Release fractions vary by package type. Most solid materials are relatively nondispersible and would be difficult to release in particulate form. Aerosol (airborne dispersed) and respirable aerosol fractions are assigned by material dispersibility category that describe the physical form of the material.

In evaluating the radiological consequences, RADTRAN 4.0 uses an atmospheric transport and dispersion model for material dispersed from an accident, and considers radiation doses resulting from the direct inhalation, resuspension, cloudshine, groundshine, and ingestion pathways.

For highway transport, three population-density zones are considered (rural, suburban, and urban). Specific locale population densities for the proposed action and alternatives were used in determing the fraction of highway distances travelled in each zone. The accident probability rates are population zone-specific due to differences in average speed, traffic density, and other factors in rural, suburban, and urban areas. The accident rates used are from DOT data for the entire commercial shipping industry, and are based on millions of total vehicle-kilometers of travel.

Representative interstate highway routes from each potential origin to each potential destination for use in RADTRAN 4.0 are generated by the HIGHWAY 3.0 routing network code, which also give fractions of travel in rural, suburban, and urban population density zones and total one-way distance (Cashwell 1989). The HIGHWAY 3.0 routing network includes the Interstate Highway system, state-designated alternate routes, and access routes to various DOE facilities. Because of their high and uniform levels of engineering and safety, the Interstate Highways have been identified by the DOT as the preferred routes for transport of highway-route-controlled quantities of radioactive materials; where available, urban beltways and bypasses are used.

To calculate total transport risk, the risk per kilometer per shipment is multiplied by the number of kilometers a shipment travels in the appropriate population density zone and by the number of shipments of that type; these products are then summed.

Similar calculations are performed for non-radiological unit-risk factors (e.g., risk of fatality from mechanical injury) to determine total nonradiological risks. Note that for these risks the two-way travel distance is used because, while radiological risk may be incurred only for a shipment containing radioactive material, nonradiological risks are equally likely when the transport vehicle is traveling empty or loaded.

A.2 MARITIME ACCIDENT PROBABILITIES AND ENVIRONMENTS

A.2.1 Maritime Accident Probabilities

Hypothetical maritime accidents can be described in a sequence as the vessel travels from the open ocean to dockside. Accidents of all severities on the open seas occur with a frequency of from 2.9×10^{-4} to 5.8×10^{-4} accidents per trip, with the lowest value being for the Atlantic Ocean and the highest value for the Gulf of Mexico. Historically, about 54 percent of all accidents in port and on the open seas are collisions (Warwick 1976). For port accidents, only about 2.5 percent involve fires (OR 1979). The remaining accidents are groundings and other non-collision accidents (Warwick 1976). Since vessels generally move on the open seas with higher speeds than in ports, collision accidents on the open seas tend to be more severe. As a vessel nears port, it enters more congested waters and speed decreases, but accident frequencies increase because of the increased ship traffic and relative proximity of one vessel to another.

The probabilities of marine accidents and their severity have been evaluated (OR 1979) and summarized in DOE/EA-0515 (DOE 1991b). This evaluation indicated that approximately 73 percent of the marine accidents reported to the U.S. Coast Guard are in inland waters. The remaining 27 percent were on the open seas. Based on collision accident frequencies in inland waters, the probabilities of various collision severity levels determined in DOE/EA-0515 (DOE 1991b) are summarized in Table A-1.

Table A-1

Probabilities for Accidents in Ports

Accident Environments in Increasing Severity Level (Net Additive)	Probability, per port call
Immersion	4.0×10^{-4}
Any collision	2.5×10^{-3}
Severe collision	1.8×10^{-4}
Severe collision impacting a given cargo hold	2.9×10^{-5}
Fire following a severe collision impacting a given cargo hold	7.8×10^{-9} to 1.1×10^{-8}

A review of actual transport experience during a 16 year period (1971 to 1985) of DOT record keeping through the Hazardous Material Incident (HMI) reporting system shows that no transport accidents in U.S. waters involving radioactive material have occurred for the water transport mode (DOE 1991b).

A.2.2 Maritime Accident Environments

A.2.2.1 Package Response to Immersion

For accidents in a port, the immersion environment is rather benign since port waters average less than 200 meters in depth. Present day salvage techniques allow for recovery of packages at depths of up to 200 meters from the sea bed (DOE 1991b). Should the Mound 1 KW Package be lost at sea in depths greater than 200 meters, long-term containment of the fuel would be expected due to the low corrosion rates of the stainless-steel used in its construction. Studies of the behavior of Pu-238 heat source components in the ocean environment indicate that the heat of radioactive decay promotes encrustation by mineral deposits from the seawater, further reducing the possibility of release (NASA 1989 and 1990). Even if a release of Pu-238 would occur, the oxide nature of the fuel results in a very low dissolution rate and the aquatic chemistry of plutonium is such that it preferentially binds with the sediment rather than remaining dissolved.

A.2.2.2 Package Response to Mechanical Forces

Collisions are among the most potentially severe accidents that occur in the region of a port. Although some groundings could be severe enough to tear the ship's hull structure and perhaps even cause flooding of some cargo compartments, groundings present less threat of mechanical damage than collisions.

In practice, for load management purposes, the packages are stowed toward the center line of cargo vessels. This practice also results in packages usually being located at least 8 meters away from the ship's hull. Past collisions in which a ship was struck broadside by a ship with a relatively rigid bow (e.g., an icebreaker) did not result in penetration that deep (8 meters) into the structure of the struck ship.

DOT regulations in 49 CFR 173 require that "each shipment of radioactive material shall be secured in order to prevent shifting during normal transportation conditions." If a package secured by tiedowns were exposed to direct forces, then the tiedowns could either fail or hold. If they failed, then the package would most likely be pushed aside rather than absorb the energy of the collision.

A.2.2.3 Container Drops During Off-loading

Another category of accident that is not related to ship collisions is container drops during handling. In a study of one port that handled large amounts of containerized cargo, involving at least 750,000 moves annually, an estimated 1 to 2 containers were dropped per year (DOE 1991b). A move is defined as an operation in which a crane picks up a container, moves it, and disengages. This amounts to an historical probability of a container drop of about 2.7×10^{-6} per year.

The berths at ports consist of concrete aprons constructed on friction pilings (driven into the sediment or bedrock) or on tamped earth contained within sheet pilings. Both are relatively yielding surfaces, and the water or the deck of a ship are even more yielding than a dock surface.

A.2.2.4 Package Response to Fire

Packages of the type to be used to transport the Pu-238 fuel are designed and tested to survive the thermal load specified in the package certification performance criteria (i.e., the thermal load from a fully engulfing fire at 1475°F for 30 minutes) with no release of contents. Creep-stress rupture of the containers would begin to occur only after the package was exposed to 1475°F for much longer periods of time. The rupture event could release a small fraction of the fuel into the primary container cavity, but would relieve the pressure buildup. Thus, unless the package also sustained mechanical damage, a significant release into the primary containment of the package would be difficult to achieve by fire alone. Furthermore, a release to the primary containment vessel does not imply a release to the environment. In the latter case, fire alone is not a credible means of causing a release and any accident sequence that resulted in a release of contents must include exposure of the same package to mechanical forces great enough to cause failure (i.e., greater than in the certification tests). As a final note, the packages will be shipped inside ISO containers that will provide additional thermal (and mechanical) protection in case of an accident.

Fires are historically a small fraction (about 2.5 percent) of maritime accidents (OR 1979). Cargo ships are equipped with fire suppression equipment to handle most fires. Historical records regarding maritime accidents indicate that while some severe fires have occurred, they represent no more than 3 percent of all ship fires (OR 1979). Severe ship fires often involve flammable liquids and may burn for many hours or days or until the ship sinks, but fires of this type occur almost exclusively on ships carrying petroleum products (e.g., oil tankers). A cargo ship carrying the Pu-238 fuel could become involved in such a fire if it was involved in a collision with a tanker, the contents of which subsequently ignited.

Since stowage regulations require that no other hazardous or flammable material be stowed with radioactive materials, the largest potential on-board source of flammable material to sustain a major fire in a cargo ship carrying the Pu-238 fuel is the ship's fuel supply. Protection provided by the Mound 1 KW Packages and the ISO containers, and the separation of the cargo from the ship's fuel would be factors that would reduce the effects of a fire. In practice, mitigating measures such as flooding a hold with water could be used to prevent packages from experiencing excessive thermal loads.

A.3 HIGHWAY ACCIDENT PROBABILITIES AND ENVIRONMENTS

The average truck accident rate for the entire U.S. is 3.1×10^{-7} accidents per kilometer (km). The average rates for the three population density zones of interest in RADTRAN 4.0 are 1.37×10^{-7} per km for rural (average of 6 persons per square km), 3.00×10^{-6} per km for suburban (average of 719 persons per square km), and 1.60×10^{-5} per km for urban (average 3,861 persons per square km), respectively. These rates are for all reported combination truck accidents on interstate highways. The accident conditions for the various severity categories are described in NUREG-0170 (NRC 1977). Eight accident categories are designated with conditional probabilities developed for the severity categories for truck shipments, ranging in severity from the lowest (category I) to the highest (category VIII). A category VIII accident is characterized by a combination of crush forces and fire duration with severity conditions would be expected in only the rarest of accidents.

The probability of the very severe accident which would be required to result in a release of radioactive material carried by an SST would be lower than the same probability for the U.S. trucking industry as a whole. For example, SSTs do not operate in poor weather conditions. Restricting truck transport to good weather conditions reduces the overall truck accident rate by about 10 percent (NRC 1977). The accident resistance provided by the SST is significant. The high integrity of the trailer acts as an impact-force-reducing barrier and provides thermal protection. The thermal protection provided by the SST is such that the SST is capable of withstanding temperatures in excess of the regulatory test-fire temperature (1475°F) for periods exceeding the test duration of 30 minutes without significant elevation of internal temperature. When the additional thermal protection of the Type B package is considered, the Pu-238 fuel would not directly experience thermal loads characteristic of a category VI fire. The SST so effectively prevents either of these conditions from affecting the payload that a category VI accident would not result in any release of contents. Lesser accident categories (I through V) would also not result in a release of material to the environment.

The generic release fractions for each accident severity category are estimated in NUREG-0170 (NRC 1977) and indicate values of 0.01 and 0.1 for categories VII and VIII, respectively. The release fractions assigned to the Type B packaging in accident severity categories VII and VIII for the packaging itself must be modified to reflect the protection afforded a shipment by the SST. For an integral transport vehicle, such as the SST, NUREG-0170 indicates no release for category VII and a release fraction of 0.1 for category VIII, thus conservatively granting no protection credit to the SST in these extreme circumstances.

Given an accident, the conditional probability of a severity category VIII for each of the three population zones of interest in RADTRAN 4.0, are 1.13×10^{-4} for rural, 5.93×10^{-6} for suburban, and 9.94×10^{-7} for urban, respectively. No transport accident this severe (category VIII) has ever been recorded (DOE 1988). The total accident probability is determined by product of the population-zone specific base accident rate times the distance travelled in each population zone (in kilometers) and the conditional probability of severity category VIII in each population zone, summed over the population zones. When nonradiological accidents involving traffic fatalities are considered, the appropriate state-specific accident rates are used. Note that in determining the nonradiological accident rate, the round trip distance is used.

A.4 APPLICATION OF RADTRAN 4.0

The RADTRAN 4.0 computer code (Newhauser, 1989) described in Section A.1 has been applied to estimate the risks (probability times consequence) resulting from transportation under both incident-free and accident conditions. Information presented for ocean and highway transport in Sections A.2 and A.3, respectively, has been used as a basis for this analysis. The parameter inputs use in this analysis are presented below.

RADTRAN 4.0 inputs related to transport link distances, population densities, and accident probabilities are those as described in Sections A.2 and A.3 for ocean and highway transport, respectively. Parameters used that are specific to the Pu-238 fuel of interest are as follows:

- TI index: 11 (20 percent due to gammas and 80 percent due to neutrons) for a single fully loaded Mound 1 KW Package with 1.04 kg of Pu-238 dioxide, corresponding to 13,100 Curies.
- Packages per shipment: 8 nominal with 10,688 Curies of Pu-238 per package (total of 85,500 Curies per shipment)
- Fuel form: plutonium dioxide powder
- Release fraction: 0.1 for accident severity category VIII
- Aerosol (airborne dispersed) fraction: 0.8
- Aerosol respirable fraction: 0.005

Parameter values used for the ocean transport phase are as follows:

• Number of crewmen	10
• Distance from source to crew (meters)	61
• Number of handlings	2
• Stop time at dock per shipment (hr)	3
• Number of persons exposed while stopped	50
• Exposure distance while stopped (meters)	50
• Storage time on dock (hr) [Note: This is conservative in that no storage on the dock prior to the transfer to SSTs is anticipated]	24
• Exposure distance during storage (meters)	100
• Number of persons exposed during storage	20
• Cargo vessel speed during voyage (km/hr)	24.2

For the port accident scenario, a severe accident probability of 1.1×10^{-8} per shipment was used. The release quantity was estimated using the same assumptions identified above for Pu-238. The population density was taken as port-specific based on USDC (1988).

Parameter values used for the highway transport phase are as follows:

• Speed in rural population zone (km/hr)	88.6

• Speed in suburban population zone (km/hr)	40.3
• Speed in urban population zone (km/hr)	24.2
• Number of crewmen	2
• Distance from source to crew (meters)	10
• Number of handlings	2
• Stop time per km (hr/km)	0.011
• Persons exposed while stopped	50
• Average exposure distance while stopped (meters)	20
• Storage time per shipment (hr)	0.0
• Number of people per vehicle on link	2
• Fraction of urban travel during rush hour traffic	0.1
• Fraction of urban travel on city streets	0.0
• Fraction of rural-suburban travel on freeways	1.0

The results of the RADTRAN 4.0 analysis of the transportation risks for the alternatives considered are presented in Appendix C for use in other portions of this EA.